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Analytic estimation and numerical modeling of actively cooled thermal protection systems with nickel alloys

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Abstract Actively cooled thermal protection system has great influence on the engine of a hypersonic vehicle, and it is significant to obtain the thermal and stress distribution in the system. So an analytic estimation and numerical modeling are performed in this paper to investigate the behavior of an actively cooled thermal protection system. The analytic estimation is based on the electric analogy method and finite element analysis (FEA) is applied to the numerical simulation. Temperature and stress distributions are obtained for the actively cooled channel walls with three kinds of nickel alloys with or with no thermal barrier coating (TBC). The temperature of the channel wall with coating has no obvious difference from the one with no coating, but the stress with coating on the channel wall is much smaller than that with no coating. Inconel X-750 has the best characteristics among the three Ni-based materials due to its higher thermal conductivity, lower elasticity module and greater allowable stress. Analytic estimation and numerical modeling results are compared with each other and a reasonable agreement is obtained.

1. Introduction

The high specific impulse enabled by air-breathing engines is a key factor in the technology for the continued development of advanced high-Mach-number aerospace flight systems. The aerothermodynamic characteristics of scramjet engines have been extensively researched, and their potential was successfully demonstrated. However, for parts of the hypersonic vehicle design, there is an urgent need for strong, lightweight, high-temperature and oxidation-resistant structures.[1–3] The combustor must endure extremely demanding

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high-temperatures (near 1000 °C) and oxidation conditions when operating at Mach 7 cruise conditions.[4–6] An actively cooled thermal protection system is a good choice to solve this problem. When the active cooling fuel flows across the panels of a combustor wall, the temperature of the engine reduces while the temperature of the fuel rises, which will improve the operating condition of the hypersonic vehicle. Continuously repeated channels of these panel-fuel-panel sandwiches allow internal fluid transport and enable simultaneous active cooling.[7–10] Due to nickel-based superalloys' high resistance to damage and the availability of relatively low-cost manufacturing approaches, they are widely used in high-temperature aerospace applications.[11–17]

Duplication of the hypersonic flight environment requires extreme temperatures and pressures coupled with complex physical interactions. So the testing and evaluation of hypersonic systems presents a unique set of challenges. Rakow and Waas[18,19] introduced and validated a novel experimental technique and load frame, which provides a significant improvement in the simultaneous preservation of thermal and mechanical boundary conditions during thermomechanical structural testing, and used it to evaluate sandwich panels with metal foam cores which are applied as actively cooled thermal protection systems in hypersonic vehicles. Langener et al.[20] used a supersonic hot-gas-flow test facility to investigate the application of transpiration cooling to ceramic matrix composite materials for scramjets. Song et al.[21] performed a transpiration cooling experiment using an optical heating method that provides a heat flux as high as 234 W/cm^2 on the surface of a specimen for a scramjet engine. Qin et al.[22–24] established a testing system and conducted an experimental study on the operating characteristics and performance of the re-cooling cycle of a hydrocarbon fueled scramjet engine with different flow, heat transfer and cracking conditions. Kumar et al.[25] investigated the thermal profile of a sandwich-type metallic thermal protection system filled with insulation over a period of 1000 s of experiments.

Ground-test facilities are limited in their ability to duplicate all salient parameters simultaneously. Datasets from flight experimentation are also limited due to airspace range requirements for long-distance flight corridors.[26] Computational techniques are a growing supplement to experiment; however, analytical models and computational techniques are extremely time-consuming, falling short of adequate fidelity, and requiring data to anchor and validate them.

Lu et al.[7] used numerical simulations to get the thermal characteristics of all-metallic sandwich structures with two-dimensional prismatic and truss cores. Vermaak et al.[27–30] developed a new processing method to study the high-temperature performance of actively cooled vapor phase strengthened nickel-based thermostructural panels and established a computational technique to determine shakedown limits for actively cooled structures that withstand extreme thermomechanical loads. Valdevit et al.[31–33] developed a material selection methodology for actively cooled rectangular panels. The procedure incorporates an analytical model for temperature and stress distributions subject to thermomechanical loads representative of hypersonic flight conditions. Pizzarelli et al.[34,35] analyzed the effect of wall heat conduction on the coolant flow by means of coupled computations between a validated Reynolds-averaged Navier–Stokes equations solver for the coolant flow field and a Fourier's equation solver for the thermal conduction in the solid material. Kontinos[36] coupled a thermal analysis method with application to metallic thermal protection panels. Bao et al.[37,38] proposed a 1D cooling channel model using unsteady partial differential equations (PDEs) and taking into account the strong dependencies of hydrocarbon fuel properties on temperature and pressure.

The literature review performed by the present authors did not yield a definite model that can properly considers the coolant flow and thermomechanical loads for actively cooled thermal protection systems with nickel alloys. As a result, the objective of this study is to establish an analytic estimation model to investigate actively cooled structures that withstand extreme thermomechanical loads. Actively cooled systems with three kinds of nickel alloys with and with no thermal barrier coating (TBC) are investigated with this model and temperature and stress distributions are obtained.

2. Model

2.1. Physical model

A typical hypersonic vehicle is shown in Fig. 1, in which we can see that the combustion chamber is surrounded by sandwich panels. The detailed structures of the sandwich panels are shown in Fig. 2. The actively cooled panels suffer extremely high thermal loads from the combustion chamber.

2.2. Thermal analysis

Four assumptions are used in this work to investigate the temperature distribution of the active cooling system, which are shown as follows:

1. The top face of the panel is exposed to hot gases at a uniform adiabatic wall temperature T_{aw} and constant convective heat transfer coefficient h_{G}.
2. The bottom face and the sides are thermally insulated. All heat from the top face is carried away by the cooling fluid.
3. The heat conduction along the length of the panel in both the channel structure and the coolant is ignored.
4. The coolant temperature is uniform at each cross section, increasing with distance Z along the panel length from an initial value T_{f0} at the channel inlet to its maximum T_{fmax} at the outlet.

We select one panel unit as the analysis unit since the actively cooled panel structure is repeated periodically. The thermal resistance network is shown in Fig. 3, where

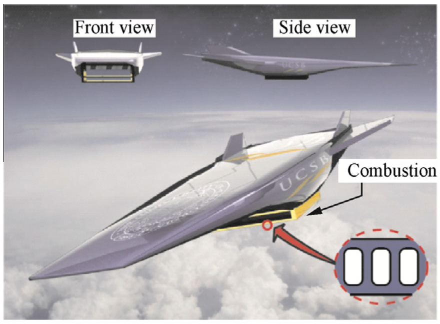

Fig. 1 A typical hypersonic vehicle photo.[32]